PHASE-INSENSITIVE RECOVERY OF CLOCK PULSES OF WAVELENGTH DIVISION MULTIPLEXED OPTICAL SIGNALS

BACKGROUND OF THE INVENTION:

1 FIELD OF THE INVENTION

[0001] This invention is directed to recovering clock pulses of wavelength division multiplexed optical signals. In particular, it relates to simultaneous clock recovery of many wavelength division multiplexed optical signals.

2 TECHNICAL BACKGROUND

[0002] As the capacity of wavelength division multiplexed (WDM) transmission systems increases in response to the increasing demand for communication, the maximum reach of each transmission system is diminished. Regenerators are therefore required at regular intervals along a transmission link in addition to any regenerators associated with network nodes where traffic routing takes place. It may be argued that regenerators are necessary within switching nodes to provide traffic routing and grooming functions, though this is not always the case when traffic on a given wavelength is routed straight through the node. However, the use of regenerators between nodes increases the network cost without contributing additional functionality. A cost-effective means of regenerating WDM signals is therefore required as an alternative to full WDM demultiplexing and opto-electronic regeneration. System manufacturers indicate that this is particularly necessary for 40Gbit/s data rate systems with a target reach of 3000km but a practical transmission limit around 1500km.

[0003] A 3R regenerator (Reamplifying, Reshaping, Retiming) is a known example of an all-optical regenerator useful for future high-speed and high-capacity transparent optical networks. All-optical clock recovery is a major building block of the 3R all-optical regenerator because clock recovery is needed for its re-timing function. Many single channel

approaches to all-optical clock recovery have been proposed and demonstrated. One single-channel clock recovery device used a fiber-optic parametric oscillator where the amplitude-modulated parametric gain for the clock signal is optical phase insensitive. Most clock recovery approaches are designed for one channel operation because for multi-channel all-optical clock recovery (MOCR), technical challenges are multiplied.

[0004] In a first MOCR approach, two-channel optical clock recovery was demonstrated using stimulated Brillouin scattering (SBS) in an optical fiber. However, due to the wavelength dependence of the Brillouin frequency shift, the total optical bandwidth effectively available to this clock recovery device is only about 3 nm. This limited spectral coverage is a severe drawback of the SBS-based MOCR. In a second approach, MOCR was achieved in an actively mode-locked fiber ring laser formed by a semiconductor optical amplifier array module integrated with two waveguide grating routers (AWGs) and an Er-doped fiber amplifier (EDFA). Several significant disadvantages exist with this approach. First, because of the homogeneous line broadening of the EDFA, the multi-channel operation of the fiber laser is inherently unstable. Second, in this device, each semiconductor optical amplifier (SOA) in the array module acts as an active mode-locker for only one corresponding channel. This increases the cost and complexity of the system. Third, no means to compensate the difference in path lengths for different channels within the SOA-AWG block were implemented, which is a requirement for multi-channel operation. Finally, overall speed of the device is still limited by the speed of the SOA response.

[0005] Therefore there is a need for an improved method and apparatus for use in all-optical clock recovery and signal regeneration, which can simultaneously process a plurality of WDM signals.

BRIEF SUMMARY OF THE INVENTION

[0006] According to a first aspect of the invention, an optically-pumped mode-locked fiber ring laser for optical clock recovery of multiple wavelength division multiplexed optical signals actively mode-locks a plurality of outputs of the laser as a plurality of recovered

clocks for a plurality of the multiple wavelength division multiplexed optical signals. The laser cavity has a cavity length corresponding to an integer multiple of bit periods of at least one of the multiplexed optical signals for receiving a pre-amplified version of the plurality of wavelength division multiplexed optical signals to provide gain modulation through a phase-insensitive parametric amplification and recirculating a proportion of the output from the laser cavity back through the laser cavity for spatially mode-locking the output of the laser cavity as a recovered clock whereby the recovered optical clock each having a periodic train of optical pulses with a repetition rate corresponding to the clock rate of the corresponding multiplexed optical signal is generated by mode-locking of the optically-pumped laser produced by a spatial modulation of the phase-insensitive parametric gain produced by the pulsed nature of the wavelength division multiplexed optical signals. A nonlinear gain medium disposed in the cavity has a sufficiently large dispersion at all of the wavelengths corresponding to the multiple wavelength multiplexed optical signals for minimizing four-wave mixing crosstalk among the multiple wavelength multiplexed optical signals, among the recovered clocks, and between the plurality of multiple wavelength multiplexed optical signals and the recovered clocks. The gain medium is pumped by the plurality of pre-amplified multiplexed optical signals to provide efficient gain modulation through the phase-insensitive parametric amplification at a plurality of narrow wavelength bands, each of the plurality of narrow wavelength bands immediately adjacent to a wavelength of a corresponding optical signal and each of the plurality of narrow wavelength bands including a corresponding recovered optical clock wavelength, and each of the corresponding optical signals copropagating in the laser cavity through the nonlinear gain medium with the recovered optical clocks. A parametric optical amplifier or a Raman amplifier having an inhomogenously broadened gain amplifies the plurality of recovered clocks for compensating a portion of the cavity loss at all wavelengths of the plurality of recovered clocks. A wavelength selector passes the light at the plurality of wavelengths of the recovered clocks for recirculation in the laser cavity and preventing the light from the multiple wavelength division multiplexed optical signals and a plurality of idler waves

generated by four wave mixing between the multiple wavelength division multiplexed optical signals and recovered optical clocks from recirculating in the laser cavity.

[0007] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the invention as described in the written description and claims hereof, as well as the appended drawings.

[0008] It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework to understanding the nature and character of the invention as it is claimed.

[0009] The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a schematic diagram of a phase insensitive parametric amplifier-based ring laser clock recovery circuit, in accordance with the teachings of the present invention;

[0011] FIG. 2 is a schematic diagram of the optical amplifier 56 of FIG. 1, implemented by a second highly nonlinear dispersion shifted fiber 33;

[0012] FIG. 3 is a graph of the gain profiles of the cavity of FIG. 2;

[0013] FIG. 4 is a schematic diagram of the optical amplifier 56 of FIG. 1, implemented as a Raman amplifier;

[0014] FIG. 5 is a graph of the gain profiles of the cavity of FIG. 4;

[0015] FIG. 6 is a graph of dispersion as a function of wavelength for the highly nonlinear dispersion shifted fiber 3 of FIGS. 1, 2, or 4, according to the invention, as compared to the single mode fiber 28 which could be used as the length of the fiber for the cavity;

[0016] FIG. 7 is a design chart for the fiber 3 of FIG. 1 where the parametric gain curve is graphed as a function of the position of the signal channel with respect to the zero-dispersion wavelength;

[0017] FIG. 8 a dispersion as a function of the wavelength design chart for the fiber 3 of FIG. 1; and

[0018] FIG. 9 displays the parametric gain bandwidth profiles excited in the parametric amplifier of FIG. 1 and the channel spacing positions for the fiber 3 of FIG.

DETAILED DESCRIPTION OF THE INVENTION

[0019] A novel approach to the multi-channel all-optical clock recovery (MOCR) was proposed by A. Ellis in a patent application entitled "Recovery of Clock Pulses of Wavelength Division Multiplexed Optical Signals" assigned to the same assignee. This approach is based on a fiber-optic parametric oscillator, in which periodically modulated gain results from the phase-sensitive FWM process in the fiber. Phase-sensitive parametric amplification operation is inherently unstable due to the cavity length shifts caused by the environment such as temperature changes. To solve this problem, gratings were proposed as a passive method to stabilize the cavity length in the same patent application. Experimental results show that the gratings can indeed maintain the cavity length matched to the clock frequencies of the input signals. However, because the cavity gain modulation resulting from the four-wave-mixing (FWM) process is optical phase sensitive, the above method may still have a technical challenge to suppress the amplitude noise resulting from a random optical phase shift between the clock and input signal. Even with the use of a non-zero dispersion shifted fiber (NZ-DSF) for multi-channel operation, the potential problem of cavity length stability may still be present. The use of an Erbium Doped Fiber Amplifier (EDFA) to compensate for the cavity loss in a multi-channel case may lead to unstable operation due to the mode competition among the channels caused by homogeneously broadened gain of an EDFA.

[0020] Due to the fundamental nature of the parametric amplification process, if all three of the pump, signal and idler optical signals are present at the input of the fiber laser ring loop,

phase-sensitive amplification only takes place if there is a specific phase relation between them. Hence, if the pump light, a signal, and the idler are all present at the input of a highly nonlinear dispersion shifted fiber (HNL-DSF1 or HNL-DSF2), the amplification process is phase-sensitive. For the phase-sensitive parametric amplifier, pump and signals are supplied from outside of the ring cavity, and idlers are circulated in the cavity, so all three are entering the nonlinear fiber at its input. Different clocks do not interact because their respective signals all have different phases. This is the advantage and the challenge of the design at the same time, because it assumes that optical signals coming from the transmission line have a well defined phase to begin with.

[0021] On the other hand, if the pump light and a signal are present at the input of a nonlinear fiber (for example a highly non-linear dispersion shifted fiber HNL-DSF1 or HNL-DSF2), the amplification process is phase-insensitive. Hence, if only the pump and signal optical signals are present in the phase-insensitive case, the phase of the optical wave does not matter, because the idler signal is generated with the proper phase, inside the amplifier automatically. In a phase-insensitive parametric amplifier cavity, only signals (which serve as a parametric pump) and clocks that are recirculated in the cavity are entering the nonlinear fiber at its input. Therefore the optical phase relation between the signals and the clocks does not matter. Idlers are still generated in the parametric process, but the idlers are thrown away by the filters (such as gratings), so that the idlers can not recirculate or get to the nonlinear fiber input.

[0022] This phase insensitive approach provides an advantage in terms of not needing to watch the phase of the optical waves. However, the advantage of the phase-sensitive design is eliminated and now signals can interact. Therefore, the other fundamental property of parametric amplification is implemented - if the pump wavelength is designed as a far longer wavelength than dispersion zero (if the medium has finite positive dispersion) than the parametric gain band is very narrow. The parametric gain would then be located only immediately left and right of the pump in spectrum. Thus, the medium (fiber) is selected with the appropriate design, and the inputs are separated far enough in wavelength, such that

each one will amplify its own clock right next to it, and never touch other signals and clocks that are far away.

[0023] Unfortunately, when the parametric gain is narrow it is also small. Thus, there is a preference for a second amplifier to boost the gain of all the clocks together almost to the level of the lasing threshold of the cavity. But that second amplifier amplifies all clocks together, so cross-gain modulation need to be minimized. Hence, the second amplifier is preferably inhomogeneously broadened.

[0024] Referring to FIG. 1, for achieving stable multi-channel all-optical clock recovery in a fiber-optic parametric oscillator, the phase-insensitive clock recovery circuit is illustrated. A signal input fiber 1 is coupled to a length of around 500m of dispersion-shifted nonlinear medium as an example of a highly non-linear dispersion-shifted fiber 3 by a coupler, such as a wavelength division multiplexer (not shown). In general, the starting point for the loop or cavity can be anywhere in a ring cavity. But, in this laser cavity example, the starting point is the input of the nonlinear fiber (HNL-DSF1) 3, because the generation of the clock signal starts there.

[0025] The output from the dispersion-shifted fiber 3 is fed to a band-pass filter 7, and the output from the band-pass filter branches into two paths. A first path from the band-pass filter 7 is coupled to an adjustable fiber delay line 9 comprising dispersion-compensating fiber having the opposite dispersion characteristics to those of the dispersion-shifted fiber 3. After the fiber delay line 9, the first path is coupled back to the signal input fiber 1 to complete an active mode-locked fiber ring laser configuration or cavity. The second path from the band-pass filter 7 comprises a clock output fiber 11.

[0026] According to the teachings of the present invention, a parametric optical amplifier 56 is disposed in the cavity. The optical amplifier 56 has an inhomogenously broadened gain for amplifying a plurality of recovered clocks for compensating a portion of the cavity loss at all wavelengths of the recovered clocks. The amplifier 56 eliminates mode competition among channels by being inhomogeneously gain-broadened and is preferably broadband to compensate for the cavity loss. Thus, the amplifier 56 achieves stable all-optical clock recovery for more than two optical channels in a single device, with the total number of

channels and spectral span limited only by the optical gain bandwidth of the amplifier 56 used to compensate cavity loss. Optcal amplifier 56 can either be a parametric or Raman amplifier.

[0027] Referring to FIG. 2, a phase-insensitive cavity loop is shown where the band-pass filter 7 of FIG. 1 is substituted by an optical circulator 23 and a grating structure, such as a plurality of chirped fiber Bragg gratings (CFBG) including gratings 25 through 31 in an optical branch 21. Furthermore, the parametric optical amplifier 56 of FIG. 1 is substituted by a wavelength division multiplexer 4 coupling a pump light input 5 at a wavelength of λp to a second highly nonlinear dispersion shifted fiber 33.

[0028] In this exemplary configuration of the multi-channel clock recovery device with parametric amplifier, the system consists of two optical couplers 2 and 35, two sections of highly nonlinear dispersion shifted fiber or gain mediums 3 and 33, one optical circulator 23, a number of chirped fiber Bragg gratings (equal to the number of channels) such as 25, 27, 29, and 31 for four multiplexed channels, one wavelength division (add) multiplexer 5, and one continuous wave (CW) pump laser source 6.

[0029] For the HNL-DSF2 or gain medium 33 (used for the parametric amplifier), the zero dispersion of the nonlinear fiber should be around the middle of the channel bandwidth which is also around the pump wavelength of the parametric amplifier. For example, if the device works for C band (1525nm~1565nm). The zero dispersion of the nonlinear fiber 33 should be around 1545nm.

[0030] Referring to FIG. 3, the operation principle of FIG. 2 is illustrated showing gain profiles where $\lambda_{s1} \ldots \lambda_{sn}$ are respectively the wavelengths of input channels 1 ... n. $\lambda_{s1} \ldots \lambda_{sn}$ are the wavelengths of recovered clocks for respectively channels 1 ... n. The center wavelength of the i_{th} CFBG (or the i_{th} channel clock wavelength λ_{ci}) is set at one of the parametric gain peaks (λ_{ci}) of the nonlinear fiber (HNL-DSF1) 3 provided by the i_{th} input channel signal (λ_{si}). As will be discussed later, by properly designing the nonlinear fiber or properly choosing the fiber length, the gain produced by each channel signal will be separated in the wavelength domain. Therefore, the gain of each clock signal is independently modulated by the corresponding input signals. To compensate for the cavity

loss, the parametric amplifier 56, consisting of a section of highly-nonlinear dispersion shifted fiber (HNL-DSF2) 33 is pumped by a high power CW light 6 on a pump input 5. When the pump light power is much larger than the power of the clock signals, the pump depletion can be neglected and the amplifier 56 works as if its gain was inhomogeneously broadened. Unlike a standard EDFA, the mode competition produced by the amplifier 56 is eliminated. When the CFBG's are properly designed, as discussed later, each channel clock can automatically adjusts its wavelength to allow the round-trip delay be equal to a multiple of the corresponding input signal bit period. Thus, a multi-channel actively mode-locked ring laser is formed through spatial modulation, where the signal gain of each resonant (clock) channel is strongly spatially modulated by only corresponding incoming channel data, and the clock signal is independently extracted from each incoming data stream.

[0031] The parametric amplifier 56, implemented by the highly nonlinear dispersion shifted fiber (HNL-DSF2) 33 is used to compensate the cavity loss. In general, the CW pump light power at the pump input 5 is much larger than the power of the recovered clock signals. Thus, the pump depletion can be neglected. The fiber 33 thus works as an inhomogeneously gain-broadened amplifier. Therefore, unlike a standard EDFA, the mode competition produced by the parametric amplifier 56 is eliminated.

[0032] To get a wide gain bandwidth which can fully cover all clock channels, the (HNL-DSF2) fiber or gain medium 33 has to be designed with a very low dispersion slope and dispersion zero wavelength as close as possible to the desired pump wavelength (λ_p). To avoid unwanted channel crosstalk, in general it is desirable to place the pump wavelength outside of the wavelength band occupied by the channel and clock signals. It is also possible to have the pump wavelength in the middle of channel signals wavelength range, as shown in FIG. 3. In this case, the subset of channels for clock recovery and pump wavelength position have to be chosen carefully so that no idler wavelength generated by parametric amplification coincides with the spectral position of another signal or clock.

[0033] The gain of the parametric amplifier 56 should be set at a level that compensates most of the cavity loss, but below the threshold of CW oscillation for all clock channels. Additional gain-flattening filters (not shown) might be required.

[0034] The control of the parametric gain bandwidth of the nonlinear fiber (HLF-DFS1) or gain medium 3 is next illustrated by FIGS. 2 and 3. Different from a phase-sensitive design, the clock recovery of the present invention uses the optical phase insensitive parametric amplification to provide the gain modulation required for active mode-locking. An extremely important advantage of phase insensitivity is that no interferometric stabilization of cavity length is required, and no restrictions are placed on the phase noise content of the input signals. However, a narrowband amplification at each clock wavelength must be realized to allow for a multi-channel operation. To avoid the cross-talk between neighboring clock channels due to overlap of the parametric gain bandwidths, the nonlinear fiber (HLD-DSF1) or gain medium 3 should be properly designed or (and) the length of fiber should be properly chosen.

[0035] The parametric gain bandwidth can be approximately expressed as

$$\Delta\Omega_A = \frac{\pi}{|\beta_2|\Omega_s L} \qquad (1)$$

where L is fiber length, β_2 is the dispersion parameter, Ω_s is the frequency shift between the pump and signal waves corresponding to the phase-matching condition. Equation (1) indicates that the gain bandwidth decreases with the increase of the dispersion parameter as well as the fiber length. Therefore, two methods can be used to control the parametric gain bandwidth of HNL-DSF1 or gain medium 3. First, the gain bandwidth is controlled by properly designing the zero dispersion point and dispersion slope of the fiber. Second, it can be easily adjusted by just changing the fiber length. Furthermore, a combination of the two methods may also be used. However, finite fiber dispersion will produce walk-off between the clock signal and input signal, which will effectively reduce modulation required for the device operation and cause the clock pulses being asymmetric. Therefore, minimum allowable channel spacing to minimize crosstalk and maximum allowable walk-off should be considered simultaneously. The walk-off should be limited within not more than 50% of the input signal pulse width.

[0036] Cavity length stabilization by using CFBG's, including 25 and 31, improves the performance of the clock recovery system. In a passive cavity length stabilization structure,

the insertion of the CFBG's into the cavity enables the laser to maintain synchronism with an external signal bit rate automatically. Since the grating is chirped, the effective reflection plane position depends on the wavelength. As a result, a small change in the cavity length or the group velocity of light can be compensated by a small shift of the lasing wavelength.

[0037] For a particular bit rate f the minimum CFBG length needed to passively stabilize the laser operation can be estimated from the following inequality:

$$\frac{nf\Delta\lambda}{c}\left(\frac{2}{D_g}-cDL_c\right)\geq 1 \qquad (2)$$

where n is the effective refractive index, c is the velocity of light, $\Delta\lambda$ is the total chirp of the CFBG, D is the average dispersion parameter of the cavity fiber, L_c is the laser cavity length and D_g is the grating dispersion, approximately given by

$$D_g = \frac{\Delta\lambda}{L_g} \qquad (3)$$

where L_g is the length of the grating.

[0038] When a different cavity length is desired for different channels, each CFBG 25 defines a unique laser cavity length for its own recovered clock signal. This means that for a multi-channel operation, there is no need to have a total cavity dispersion exactly equal to zero.

[0039] For spectral selection, CFBG's 25 and 31 combine the functions of reflection and spectral filtering. Each CFBG 25 or 31 reflects a corresponding restored channel clock signal and passes through light at all other wavelengths, including the CW pump 6, ASE, FWM terms etc., which eventually are leaving the laser cavity. Individual reflection peaks can be easily adjusted by straining or temperature-tuning corresponding CFBG's 25 or 31.

[0040] For a phase-insensitive loop with a Raman amplifier, two configurations are illustrated. The first one is the same as the loop configuration shown in FIG. 2, which could also be implemented as a Sagnac laser configuration, except that the CW pump light of HNL-DSF2 medium 33 is pumped at a Raman pump wavelength of FIG. 5.

[0041] Referring to FIG. 4, the second Raman amplifier configuration is shown. The parametric amplifier 56 of FIG. 2 is substituted by a Raman amplifier using the two Raman pump sources, coupled by two separate couplers, such as wavelength division multiplexers 41 and 42, and the gain medium 3 which could be a holey fiber, a photonic band gap fiber, a Raman fiber, or any other type of highly nonlinear dispersion shifted fiber. In general an inhomogeneously broadened gain amplifier can be either a parametric amplifier or a Raman amplifier. In other words, a parametric amplifier is not a Raman amplifier. But when a nonlinear fiber is pumped by both a parametric pump light and a Raman pump light, this nonlinear fiber can be a Raman amplifier as well as a parametric amplifier. Thus, the same nonlinear fiber (HNL-DSF) or gain medium 3 serves as the nonlinear medium for both parametric gain modulation and Raman amplification. In general, the CW pump light power is much larger than the power of the clock signals, and therefore the pump depletion can be neglected. In addition, the Raman amplifier gain is at least in part inhomogeneously broadened. Therefore, unlike when using a standard EDFA, the mode competition produced by the amplifier is eliminated. All other design issues are the same as discussed with FIGS. 2 and 3.

[0042] Hence, the present novel clock recovery device is especially designed to solve the challenges of instabilities coming from both mode competition among the channels and cavity length shift for multi-channel operation. First, to eliminate mode competition among channels, the broadband parametric optical amplifier 56 implemented by a second fiber 33 of FIG. 2 or, alternatively, a Raman optical amplifier with the two pump sources 61 and 62 is used to compensate for the cavity loss.

[0043] Using phase-insensitive parametric gain, no interferometric cavity stabilization is required, and no restrictions are placed on the phase noise of the incoming signals. Compared with semiconductor based clock extractors, the phase insensitive loop can work at much higher bite rates due to the extremely fast response time of fiber nonlinearities.

[0044] Because the phase insensitive design employs a number of chirped fiber Bragg gratings (CFBG's), such as gratings 25 and 31 in the laser cavity to automatically compensate environmental cavity length change by the small shift of the lasing wavelength,

passive locking of the output pulse repetition rate to any input clock frequency is enabled. Since the parametric gain is optical phase insensitive, this phase insensitive design is also free from the noise caused by a random signal phase variation.

[0045] Referring to FIG. 6, the typical dispersion curve of the dispersion shifted highly nonlinear fiber 3 is depicted. The highly nonlinear dispersion shifted fiber 3 is designed to have a zero dispersion wavelength outside the C band (1535 nm-1570 nm) and preferably on the shorter wavelength side. The optical effect used with the fiber 3 is the four-wave-mixing based harmonic mode locking of a parametric laser in a ring cavity configuration of FIGS. 1, 2, or 4. The parametric gain manifests itself when a pump and a signal are present at the input of the fiber and in particular on the input of a dispersion shifted fiber 3. Regardless of phase sensitive or phase insensitive, the efficiency of the parametric gain is related to the phase matching conditions between the signal and the pump and to the nonlinear coefficient of the fiber. The parametric gain bandwidth depends on the interplay between the phase mismatch and the nonlinear effect induced phase shift and is narrower when the pump wavelength is far from the zero dispersion wavelength. The peaks of the gain will be observed at wavelengths where group velocity dispersion phase shift is compensated by the nonlinear phase shift i.e. $\Delta k = -2\gamma P$ where γ is the nonlinear coefficient, P is the pump power and Δk is the group velocity dispersion phase mismatch. At the same time, in linear chromatic dispersion approximation, $\Delta k \propto D_\lambda (\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2$, where D_λ is the slope of dispersion at zero dispersion wavelength, λ_p is the pump wavelength, λ_s is the signal wavelength and λ_0 is the zero dispersion wavelength. The bandwidth of the parametric gain for different pump positions is represented on FIG. 7.

[0046] Far from the zero-dispersion wavelength, the parametric gain has a narrow bandwidth. This fact is used in the phase insensitive design to construct a multi-wavelength clock recovery system for several channels. Each cannel is used as a pump for a narrow bandwidth phase insensitive parametric process. The narrow gain from the Bragg gratings 25 or 31 insures that no significant cross talk between the extracted channels will be observed.

[0047] If, for instance, two different channels are presented at the input 1 of the fiber ring laser of FIG. 2, each of them will serve as a pump in a parametric process. In the nonlinear fiber 3 the two pumps create conditions for parametric amplification and amplify the incoming noise. The two Bragg gratings 25, 31 and the circulator 23 insure that the two wavelengths, for Signals 1 and Signals 2 for example, make full cavity round trips and are present at the input of the nonlinear fiber 3 at the same time slots when the plurality of wavelength division multiplexed optical output signal channel's "zero" and "ones" enter the cavity as input 1. These two wavelengths for Signals 1 and 2 will be amplified by the incoming "ones" and after several round trips, lasing conditions for the two wavelengths will be established.

[0048] For this lasing condition to be fulfilled, the cavity resonance frequency should be synchronized to the incoming signal data bit rate. In theses conditions, harmonic mode locking of the ring laser by the incoming signals will be established.

[0049] The parametric gain in the nonlinear fiber 3 is the mechanism that insures the lasing action after several cavity round trips and a certain number of incoming "ones" from the output channels. The clock extraction mechanism is based on the fact that the laser action of the parametric cavity is a result of a mode locking that allows the averaging of the time position of the incoming pulses and to reduce in this way the incoming jitter.

[0050] One critical point of multi-wavelength clock recovery is the number of arriving "zeros" that will switch off the lasing action and this critical parameter should be carefully calculated depending on the precise cavity configuration, whether it is a Sagnac laser or another loop configuration.

[0051] The preferred fiber is made by Germanium co-doping of the core region and with Fluorine co-doping of the depressed cladding region. Both Plasma Chemical Vapor Deposition (PCVD) and Modified Chemical Vapor Deposition (MCVD) methods can produce such fiber profiles. The fiber proposed is an "α–profile type fiber". The alfa values of the proposed design is $\alpha = 5$. The inner core radius is 2.5 μm The inner core maximal refractive index is 1.485. The depressed cladding refractive index is 1.451. The depressed cladding radius is 3 μm. The outer cladding refractive index is 1.457 at the silica level. The

calculated fiber dispersion is given on FIG. 8. The zero dispersion wavelength is at 1.4415 μm. The slope of dispersion at the zero dispersion wavelength is 0.07 $ps/km/nm^2$. The effective mode field area at 1.55 μm is 15 μm^2.

[0052] The fiber dispersion and slope of dispersion can be used to model the parametric gain bandwidth in this fiber 3 by numerical solution of the Shrödinger equations in the amplification regime. The gain curves of FIG. 9 are calculated for the case of traveling wave amplification configuration. Different input signal wavelengths were used in order to estimate the possible practical implementation of the clock recovery system in terms of channel spacing. The signal input power of each signal was equal to 10 mW. The length of the fiber used is 1 km. The parametric gain bandwidth in this case imposes the recovered channel spacing. This channel spacing for the fiber designed here is of the order of 2 nm. The 2 nm distance between the recovered channels will be insured by proper design of the Fiber Brag Gratings 25 and 31 of FIGS. 2 and 4. This channel spacing allows clock recovering at 40 Gbit/s and higher data bit rates.

[0053] To understand the phase insensitive design, the more general parametric amplification design, including the move often used phase-sensitive design is described here for more background information. For the phase sensitive design, the pump input fiber 5 pumped by a laser 6 is also coupled to the dispersion-shifted fiber 3 by a second wavelength division multiplexer (not shown). The pump input fiber 5 feeds pump radiation into the length of dispersion-shifted fiber at the wavelength of zero-dispersion. This wavelength is selected because it ensures efficient parametric amplification within the fiber for signals symmetrically spaced either side of the wavelength of zero dispersion. On start up, RZ WDM data signals are fed to the signal input fiber 1, and these pass into the dispersion-shifted fiber 3. As the pump radiation and data signals pass through the dispersion-shifted fiber, new signals known as idler waves are generated symmetrically about the pump wavelength by the process of four-wave mixing. Each pulse of these idler waves corresponds to a data one of one of the original data signals, while no pulse is generated for a data zero. As the signals and idler waves continue to travel through the dispersion-shifted fiber 3, they are each subject to parametric amplification from the pump. After passage

through the dispersion-shifted fiber 3, the remaining pump radiation and WDM data signals are blocked from further transmission by the band-pass filter 7, while the idler waves pass unhindered through the filter. A proportion of the idler wave radiation passes along the first path from the band-pass filter through the adjustable fiber delay line 9 and is re-introduced into the signal input fiber 1. The remainder of the idler wave radiation passes along the second path from the band-pass filter to the clock output fiber 11.

[0054] By suitable adjustment of the fiber delay line 9, the idler waves passing along the first path from the band-pass filter 7 return to the signal input fiber 1 in phase with the WDM data signals fed to the signal input fiber. As the idler waves and data signals now pass through the dispersion-shifted fiber 3, the existing idler waves are strongly parametrically amplified by the pump radiation as well as by the incoming data signal in the case of a data one. Furthermore, where idler waves have not previously been generated, they are generated as described above by the ones within the incoming data signal. In this way, a mode-locked ring laser is formed, where the cavity gain is strongly modulated by the temporal profile of the incoming data, and the re-circulating clock pulses are distinguished from spontaneous noise through phase-sensitive parametric amplification and other nonlinear processes within the cavity.

[0055] Parametric amplification is phase sensitive, and it is necessary to ensure that the phase of the recovered clock lines up at the input to the amplifier after each recirculation. In order to achieve this, it is necessary to have well defined phase relationships between the data and pump signals, which in practice implies that each of the signals should be well defined in terms of phase. This translates to a requirement that the coherence length of the signals be longer than several recirculations of the clock recovery loop. Faster phase variations will destroy the phase matching condition of the cavity, whilst significantly slower phase variations may be tracked by the clock recovery laser automatically adjusting its phase. In practice, for a 1km cavity, a continuous wave (pump) linewidth of somewhat less than 20kHz would be required to give a 10km coherence length. Similar constraints apply to the data signal, where the phase noise contribution of any in-line optical amplifiers should be taken into consideration. In this case, provided the ASE induced phase noise is

small (<$\delta\pi$) the ring laser will sample the average phase. This may however set a more stringent upper limit on regenerator spacing than considerations of amplitude noise.

[0056] To ensure that the re-circulating idler waves return to the signal input fiber 1 in phase with the incoming data signals, the cavity length should correspond to an integer multiple of bit periods of each of the multiplexed signals (accurate to 1% of a bit period). For a sufficiently short cavity this may be achieved with sufficient accuracy simply by adjusting the cavity length to match the central channel using the adjustable fiber delay line 9. In this respect, a sufficiently short cavity is one where the cavity length L meets the following requirement:

$$L << \frac{\tau}{2D'N_{ch}}\left(\frac{c}{\lambda^2 \Delta f}\right)^2$$

where τ is the clock pulse width, D' is the net cavity dispersion slope, N_{ch} is the number of multiplexed channels in the input signal, c is the velocity of light, λ is the recovered clock wavelength and Δf is the channel spacing. Active stabilization could be incorporated to compensate for environmental fluctuations which could affect the virtual cavity length. Provided some residual dispersion exists in the cavity, accompanied by excess self phase modulation to broaden the pulse spectrum slightly, then within its allocated channel, each recovered clock may slightly adjust its operating wavelength (and hence effective cavity length and so relative phase) to ensure maximum gain. This process is analogous to guiding filtering within soliton transmission systems, the stable operating point in this case being whichever wavelength gives the correct phase. The cavity dispersion should be carefully chosen such that several π of phase adjustment are available to the laser whilst maintaining good phase matching at the level of the data rate. In the case of phase sensitive amplification, this ensures phase matching to both the clock (radio frequency) phase of the data signal, and the optical phase of the optical carriers.

[0057] For a longer cavity, the quadratic dependence of the group delay precludes the correct cavity adjustment for simultaneous wavelengths. In this case, dispersion compensation could also be employed to enable correct cavity length adjustment for a

greater range of simultaneous signal wavelengths, for example using a fiber having mirror image dispersion characteristics to those of the dispersion-shifted fiber.

[0058] In order to suppress spontaneous noise generated through spontaneous processes within the cavity and through parametric amplification of incoming amplified spontaneous emissions (ASE), the net small signal gain should be maintained below unity. Under these circumstances, several circulations of the idler waves around the cavity are sufficient to allow stable clock recovery.

[0059] The parametric amplification process is instantaneous, and so the full saturated output power is available at any given time. So in single channel operation, the energy of each pulse is stabilized by the gain medium. This is in contrast to the case of doped fiber amplifiers, where the long lifetime precludes pulse stabilization by these means, leading to instabilities in the pulse amplitudes. The instantaneous gain may also stabilize the clock pulse amplitudes in the case of multi-channel operation. However, it is possible that two clock pulses may be present simultaneously, giving rise to small levels of saturation induced crosstalk, and potential amplitude instability. To combat this, the cavity could include a weak periodic filter, such as an etalon (parallel plate interferometer), with a free spectral range equal to the wavelength spacing of the channels. In combination with self-phase modulation induced spectral broadening, the spectral compression offered by such a filter would tend to stabilize the pulse amplitudes.

[0060] Stimulated Billouin scattering (SBS) sets a severe limitation on the pump power levels that may be propagated in an optical fiber. The threshold for SBS is typically tens of milliwatts, whilst the threshold for parametric amplification is of the order of a few hundred milliwatts. To alleviate this constraint, the fiber may be designed in such a way as to increase the SBS threshold, allowing increased power levels. Alternatively, the signal could be provided with some degree of phase modulation to increase the spectral width of the pump light beyond Brillouin gain bandwidth (~80MHz). However, in this case it is necessary to maintain a well-defined phase relationship between the three signals. Consequently, any phase modulation designed to reduce SBS must take this requirement into account. This may be achieved by modulating the phase of the pump at an integer

multiple of the frequency of circulation of one of the optical signals through the cavity, for example at the bit rate of the signal.

[0061] A second constraint relates to the amplitude of the phase modulation. Due to the walk-off between the data and pump signals over the length of the amplifier, the phase matching will be reduced. Indeed, for a π phase change the amplification will be transformed to attenuation with disastrous results. Ideally, the peak phase shift along the length of the amplifying fiber will be a small fraction of π. This implies either that the amplitude of the applied phase modulation is less than π, or that the amplifying fiber represents a small fraction of the overall cavity length and the modulation frequency matches the cavity round trip.

[0062] In view of the rather long overall cavity length, the fiber laser output is inherently unstable owing to fluctuations in the signal polarization state caused by mechanical vibration and temperature variation, as well mode competition between the two orthogonally polarized modes. In order to eliminate noise coming from the polarization fluctuations and mode competition between orthogonally polarised modes, the laser cavity may be constructed entirely with polarization maintaining (PM) fibers and PM components. The axes may be swapped at regular intervals to reduce walkoff, if necessary. The polarization sensitivity of the parametric gain ensures that the recovered clock polarization is matched to the incoming signal polarization.

[0063] The parametric amplifier should be designed to reduce crosstalk, both from the parametric amplification itself and from other four wave mixing components. If the signals (incoming data signals marked d and recovered clock signals marked c) are located within a band of width N, which is offset from the pump wavelength p by a spacing of at least 2N, then all four wave mixing products originating from any two signals and the pump fall into the zones marked FWM. There are two beneficial consequences to this design:

the signals fall outside the wavebands for either the data or the clock;

the signals are poorly phase matched, and so are of low intensity.

[0064] Four wave mixing between three data (clock) signals or two data (clock) signals and a clock (data) signal will fall into the signal band. However, since the intense pump is not

involved, the intensity of the generated signals will be low. The parametric gain bandwidth depends upon the phase matching conditions, and the parametric amplifier must be designed to take this into account. To achieve this low crosstalk level, it is necessary to have a dispersion slope above a certain critical value, and there is clearly a trade-off between channel bandwidth and crosstalk.

[0065] For this amplifier design, the obtainable recovered clock pulse widths (assuming RZ data with a 50% duty cycle and sinusoidal pulse profiles) can be calculated either by simply considering transform limited pulses with spectral widths equal to the gain bandwidth, or by using standard mode locking theory. Acceptable performance is achieved for operation at 10 or 20 Gbit/s with a 100GHz channel spacing. It is notable that this example requires a maximum wavelength shift from channel 1 to channel 16 of 75nm at 10Gbit/s with 100GHz spacing. Alternatively, each regenerator site could contain a small number of such parametric regenerators to reduce the number of channels and so alleviate the parametric gain bandwidth requirement at each site. The group velocity dispersion experienced by high channel numbers may be minimized by reducing the dispersion slope. The optimum dispersion slope, taking the two constraints into account, can therefore be determined.

[0066] A second parametric amplifier may be used to facilitate an interaction between the data signal and the recovered clock to provide a regenerator capable of re-amplifying, re-shaping and re-timing wavelength division multiplexed optical signals. The regenerator shown employs a second embodiment of a clock recovery circuit according to the invention. When the band-pass filter 7 and adjustable fiber delay line have been replaced by an optical branch 21 connected to the optical cavity between the dispersion-shifted fiber 3 and the clock output fiber 11 by means of an optical circulator 23, the optical branch 21 presents a series of cascaded chirped fiber Bragg gratings 25, 27, 29, 31, each of which is positioned at a carefully selected location along the optical branch 21 as described below and designed to reflect radiation of a particular wavelength corresponding to a respective WDM channel.

[0067] As described above with reference to the phase sensitive case, the pump input fiber 5 feeds pump radiation from pump laser 6 into the length of dispersion-shifted fiber at the wavelength of zero-dispersion via a wavelength division multiplexer 4. On start up, RZ

WDM data signals are fed to the signal input fiber 1, and these pass into the dispersion-shifted fiber 3 via another wavelength division multiplexer 2. As the pump radiation and data signals pass through the dispersion-shifted fiber 3, idler waves corresponding to the different WDM signal channels are generated symmetrically about the pump wavelength and amplified as described above. After passage through the dispersion-shifted fiber 3, the idler waves, remaining pump radiation and original WDM data signals pass into the optical branch 21 via the optical circulator 23. Each Bragg grating reflects idler wave radiation corresponding to a particular WDM channel (a restored channel clock signal) and passes through light at all other wavelengths, including the remaining pump radiation, the original WDM data signals and any amplified spontaneous emission and four wave mixing terms, which eventually leave the laser cavity. The restored channel clock signals are thus reflected back to the circulator 23 and fed back towards the clock output fiber. A proportion of the restored channel clock signal radiation is re-circulated to the dispersion-shifted fiber 3, while the remainder passes to the clock output fiber 11.

[0068] The use of chirped fiber Bragg gratings in this manner presents a number of advantages. The position of each chirped fiber Bragg grating along the optical branch 21 of the clock recovery circuit defines a unique laser cavity length for its own recovered clock signal. This means that there is no need to have a total cavity dispersion exactly equal to zero. If necessary, variable delay lines (for example in the form of fiber stretchers) can be provided between Bragg gratings (not shown) to adjust each of the individual cavity lengths.

[0069] The chirped fiber Bragg gratings combine the functions of reflection and spectral filtering. Individual reflection peaks can be easily adjusted by straining or temperature-tuning corresponding Bragg gratings.

[0070] Because nonlinear effects in silica-based glass are relatively weak, a long length of fiber (typically, hundreds of meters) is needed in order to let the system operate at reasonable power levels for both pump and signal light. As a consequence, the fiber laser operation is inherently unstable owing primarily to the cavity length changes caused by temperature variation. The insertion of the CFBGs into the cavity enables the laser to maintain synchronism with an external signal bite rate automatically. Since the grating is

chirped, the effective reflection plane position depends on the wavelength. As a result, a small change in the cavity length or the group velocity of light can be compensated by a small shift of the lasing wavelength.

[0071] For a particular bit rate f the minimum CFBG length needed to passively stabilize the laser operation can be estimated from the following inequality:

$$\frac{nf\Delta\lambda}{c}\left(\frac{2}{D_g} - cDL_c\right) \geq 1 \qquad (1)$$

[0072] where n is the effective refractive index, c is the velocity of light, □□is the total chirp of the CFBG, D is the dispersion parameter of the cavity fiber, L_c is the laser cavity length and D_g is the dispersion parameter of the grating, approximately given by

$$D_g = \frac{\Delta\lambda}{L_g} \qquad (2)$$

where L_g is the length of the grating. Since for maximum FWM gain parametric laser needs to be pumped close to the fiber zero dispersion point, D is typically very small, the second term in parentheses can be neglected and (1) simplifies to:

$$\frac{2nfL_g}{c} \geq 1 \qquad (3)$$

which has a very simple interpretation – the CFBG needs to be at least half as long as the physical spacing of two optical pulses in the fiber following at the signal clock rate. In this case, reflection from one end of the grating is delayed in respect to the reflection from the other end of the grating by a full bit period, and phase change of ±180° for the recovered clock signal can be attained by a wavelength shift.

[0073] The parametric gain bandwidth is determined by the spectral width of the corresponding incoming RZ signal. Therefore, in case of the incoming RZ consisting of perfect transform-limited optical pulses, any wavelength change in the restored clock signal would mean a significant decrease in the available gain. However, real transmission line signals will always be slightly broadened by transmission fiber nonlinearities, and they will experience additional spectral broadening due to the intra-channel FWM and self-phase modulation in the clock recovery amplifying fiber itself. We estimate that at least a 0.2 nm

wavelength shift without a significant drop in the parametric gain should be permissible for the 40 GHz clock rate.

[0074] Another important point relates to grating dispersion. For the 1 cm long grating (the minimum length needed to stabilize the 10 Gb/s clock recovery, as shown above) with a total chirp of 0.2 nm, the grating dispersion would be roughly 500 ps/nm. It might seem that such a large dispersion would make circulation of a short pulses in a laser cavity impossible. The following simple illustration shows that this is not necessarily true. Let us consider a monochromatic optical wave sinusoidally modulated with 100% modulation depth, which is the simplest form of a clock signal:

$$P = A(1+\cos\Omega t)\cos\omega t \tag{4}$$

where ω is the carrier frequency and Ω is the modulation (clock) frequency. As is well known, the spectrum of this signal is represented by the main peak at carrier frequency and two additional peaks at $\pm\Omega$, which can be shown by the transformation of (4):

$$P = A\cos\omega t + \frac{A}{2}\left(\cos(\omega+\Omega)t + \cos(\omega-\Omega)t\right) \tag{5}$$

[0075] When this signal is reflected from a chirped grating, effective reflection planes for all three spectral components will be different. At least for the case of linearly chirped grating, the amount of phase shift θ of frequency sum and difference components in respect to the carrier frequency component will be the same with an opposite sign. The resulting signal is represented by:

$$P_{refl} = A\cos\omega t + \frac{A}{2}\left(\cos((\omega+\Omega)t+\theta) + \cos((\omega-\Omega)t-\theta)\right) \tag{6}$$

which is easily transformed into:

$$P_{refl} = A(1+\cos(\Omega t+\theta))\cos\omega t \tag{7}$$

[0076] As is evident from (7), reflection of our simple example signal from a chirped grating, no matter how large the dispersion, results in a phase shift of the modulating signal, but does not cause the distortion or change the shape of that modulating signal.

[0077] In a practical mode-locked laser, large cavity dispersion can cause the laser output pulses to be chirped. But, this can be easily corrected by a length of a fiber with the right dispersion sign or a CFBG-based compensator.

[0078] For a multi-channel device, due to the wavelength dependence of the parametric gain, recovered clock signals of different channels will normally have different amplitudes. If desired, those amplitudes can be easily equalized by varying the reflection strength of the corresponding CFBGs.

[0079] Since the proposed clock recovery device operation is based on parametric amplification, it is desirable to have the pump radiation as close as possible to the zero dispersion wavelength of the amplifying fiber. Operation in the vicinity of zero dispersion, however, will also cause unwanted four-wave mixing between all spectral components present in the laser cavity and result in some amount of inter-channel crosstalk. Since the pump is the most powerful signal in the cavity, the most harmful interference will come from mixing of the pump and recovered clock signals. Therefore, it is undesirable if the pump wavelength is the same as one of the standard channel wavelengths, or if the pump wavelength is separated from any one of the channel wavelengths by an exact multiple of the channel spacing.

[0080] The most advantageous position for the pump wavelength is right in the middle between two adjacent channel wavelengths. As an example, the scheme shown in Figure 7 might be considered, wherein the pump wavelength lies mid-way between two adjacent standard channel wavelengths. This scheme has two additional advantages. First, wavelength space both to the left and right of the pump is used to allow more channels to be recovered. And second, RZ signals and recovered clocks occupy correspondingly odd and even standard channel wavelengths, which means that they can be combined (or separated) by commercially available devices known as interleavers. Of course, the scheme where all RZ signals are on one side of the pump and all recovered clock signals on the other can also be used, but it might still be necessary to only supply every other channel of the WDM system for recovery to minimize excess FWM terms and related crosstalk.

[0081] One of the major issues with harmonically mode-locked fiber lasers is so-called supermode noise. In simple terms, with the laser cavity several hundred meters long, longitudinal mode spacing is less than 1MHz. A lot of supermodes exist within a channel bandwidth, and mode competition among these supermodes causes large amplitude fluctuations of the generated optical pulses. The proposed laser is capable of automatically maintaining synchronism to an external clock despite drifts in cavity length owing to the use of CFBG, even in the absence of interferometric stabilization. Therefore, an optical filter with comb-like transmission and a free spectral range (FSR) equal to the clock frequency or a subharmonic of the clock frequency of the input signals can be inserted into the cavity to select only one or a limited subset of supermodes, thus suppressing supermode noise. The optical filter with comb-like transmission spectrum can be a fiber loop interferometer, conventional Fabry-Perot filter or an FBG-based Fabry-Perot filter.

[0082] Instead of dispersion-shifted fiber, the non-linear medium could comprise KTP crystal, a semiconductor optical amplifier or a PPLN as would be clear to those skilled in the art of optical regenerator design.

[0083] It will be apparent to those skilled in the art that various modifications to the preferred embodiments of the invention as described herein can be made without departing from the spirit or scope of the invention as defined by the appended claims. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.